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A global blockchain for recording high rates of COVID-19 vaccinations

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ABSTRACT

Blockchain has been recently proposed to securely record vaccinations against COVID-19 and manage their verification. However, existing solutions may not fully meet the requirements of a global vaccination management system. These requirements include the scalability required to support a global vaccination campaign, like one against COVID-19, and the capability to facilitate the interoperation between the independent health administrations of different countries. Moreover, access to global statistics can help to control securing community health and provide continuity of care for individuals during a pandemic. In this paper, we propose GEOS, a blockchain-based vaccination management system designed to address the challenges faced by the global vaccination campaign against COVID-19. GEOS offers interoperability between vaccination information systems at both domestic and international levels, supporting high vaccination rates and extensive coverage for the global population. To provide those features, GEOS uses a two-layer blockchain architecture, a simplified byzantine-tolerant consensus algorithm, and the Boneh–Lynn–Shacham signature scheme. We analyze the scalability of GEOS by examining transaction rate and confirmation times, considering factors such as the number of validators, communication overhead, and block size within the blockchain network. Our findings demonstrate the effectiveness of GEOS in managing COVID-19 vaccination records and statistical data for 236 countries, encompassing crucial information such as daily vaccination rates for highly populous nations and the global vaccination demand, as identified by the World Health Organization.

1. Introduction

The recent global vaccination campaign has been shown effective in curbing the COVID-19 pandemic. This disease, caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has threatened the health of millions of people worldwide and the global economy [1]. SARS-CoV-2 is remarkably infectious and, in many cases, deadly [2–5]. With time, it mutates into new strains that further exacerbate the containment of COVID-19 [6–10]. As a response, a fast and global vaccination campaign has been executed.

In this campaign, multiple vaccines have been administered to the world population [11–13]. Initially, the recommendation was for individuals to receive one or two doses of the COVID-19 vaccine to establish immunity. For those who have already been vaccinated, it is now advised to consider a booster vaccine to reinforce waning immunity to combat the emergence of new virus strains. Effective management and meticulous record-keeping are crucial in handling the increased pace of vaccinations. Inadequate management of COVID-19 vaccination records can create opportunities for the production of fraudulent records, counterfeit vaccines, and illicit activities. Such lax management undermines community health efforts, facilitates virus mutation, and increases the likelihood of implementing stringent preventive measures across different regions of the world [14,15].

Global access to electronic records can leverage the tracking of vaccination progress, the management of preventive measures, and the detection of zones where the disease spreads rapidly [16,17]. However, the adoption of electronic health records (EHR) is not free of challenges, controversies, and risks [18]. Moreover, compliance with various health offices is to be ensured. For example, the United States President Council of Advisors on Science and Technology (PCAST) identified several critical requirements of EHRs [19]: (a) interoperability between EHR systems for secure sharing of patient data, (b) flexibility in the design of EHR systems, (c) low implementation costs, (d) privacy, and security need to be considered. As a response to those requirements, the PCAST report suggests standardizing the implementation of EHR and recommends the disaggregation of EHRs using a single universal exchange language (UEL) for exchanging medical data

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and making patient records available to authorized persons anywhere, anytime via the Internet. These measures may improve interoperability and usability and provide continuity of care (COC) [20].

Blockchain, an immutable ledger, has been proposed for implementing accessible EHRs [21,22]. It offers data immutability, availability, access control, and authentication to address challenges associated with electronic vaccination records. Immutability is achieved through distributed record copies and a consensus algorithm, where independent validator nodes in a network agree on adding data records. This consensus process prevents collusion or record alteration by adversarial nodes. Validators communicate through a peer-to-peer (P2P) network to execute the consensus process.

Despite their advantages, the use of EHRs for vaccination records during the COVID-19 pandemic has also raised concerns. One of them is privacy, as the misuse of electronic vaccination records could lead to increased surveillance and compromise the privacy of an individual [23]. Another one is that EHRs may be used for enforcing policies of vaccination compliance and in turn exacerbate existing inequalities against marginalized or vulnerable populations [24]. Or it could cause unnecessary delays for those traveling abroad on verification systems that are subject to innefficient management [25]. While these concerns must be considered, we focus on whether blockchain can be scalable enough to satisfy global demands.

Current blockchain-based vaccination record solutions adopt a single-layer blockchain architecture and that limits their capacity to support the recording of vaccination records on a global scale [26–30]. A complex consensus algorithm exacerbates these limitations. A global blockchain must be able to keep up with the daily vaccination rates of the most populous countries. To achieve that, blocks must be quickly added to the blockchain [31]. Equally important, the blockchain must leverage the interoperation between national blockchains and the exchange of information on vaccination records among them while supporting their autonomy [32–34]. Such an exchange permits the aggregation and analysis of vaccination statistics for the benefit of international health stakeholders.

To support these objectives, we propose GEOS, a scalable global vaccination information system based on blockchain technology. GEOS is a two-layered blockchain system that enables interoperability among national vaccination information systems on a global scale. The use of extensible data exchange formats and verification protocols that ensure the secure recording and sharing of immutable vaccination data leverages interoperability. GEOS also supports system usability by adopting applications that record vaccination as smart contracts for secure data recording and retrieval. The scalability of GEOS is achieved through its layered architecture and a low-complexity consensus algorithm that utilizes the Boneh–Lynn–Shacham (BLS) signature scheme while maintaining resilience against Byzantine attacks [35].

We model the latency of the communications performed during the consensus process and evaluate it in terms of block and transaction confirmation times and transaction throughput for recording vaccination data. We show that GEOS adheres to the current recommendation of 2.5 doses per person to support the vaccination of the global population per year and the daily vaccination rates in the most populous countries, such as China and India.

2. Related work

Blockchain has been increasingly considered a promising solution to various existing challenges in healthcare. Such challenges are data privacy, integrity, broad access, secure sharing of EHRs, and management of vaccine production, distribution, and administration [36–41].

Blockchain technology is being employed in the pharmaceutical industry to address critical concerns such as drug counterfeiting, cloning, tracking, and authenticity. By leveraging blockchain, the industry aims to enhance drug management throughout the entire supply chain, ensuring efficient and secure processes at every stage. Specifically, the use of blockchain has been considered for combating counterfeit drugs and vaccines [42], managing drug and vaccine supply chain [43] and inventory [44], and supporting drug traceability [45] and recalls [46].

Vaccine manufacturers and public health agencies may use blockchain to enhance transparency and effectiveness in vaccine production and distribution. Yong et al. [47] designed a blockchain for vaccine supply and supervision. Lopez et al. [48] and Antal et al. [28] each proposed a blockchain to distribute COVID-19 vaccines.

The immutability property of blockchain could also ease the implementation of access control mechanisms [49], the secure sharing [50, 51], management [52] and distribution [40] of medical data, efficient management of EHR, and monitoring and tracking of emerging infectious diseases. It has also been used to preserve the privacy of GDPR-compliant COVID-19 tests and vaccine certificates [30] and the alteration of the recording of COVID-19 cases and deaths [53]. Combining blockchain with artificial intelligence has been proposed to manage self-testing and tracking COVID-19 [54] and to detect outbreaks [55].

As a global vaccination recording system, blockchain has been proposed to provide real-time access, secure sharing of data among countries, and data privacy of vaccination records. Abuhashim et al. [27] proposed Block-VC, a global blockchain to share vaccination records among countries. Similarly, Alabdulkarim et al. [56] proposed a blockchain for sharing COVID-19 information among countries. Loss et al. [29] proposed a blockchain system for secure interoperability among health systems to share COVID-19 data. Biswas et al. [57] presented GlobeChain, a blockchain architecture for real-time cross-border medical exchange services about COVID-19.

A summarized review of related work on blockchain-based vaccination systems is presented in Table 1. Existing proposed blockchains might not satisfy the demands of the most populous countries or the global population. The solution based on a consortium blockchain and Proof-of-Authority [26] suffers from a long transaction confirmation time, which makes it impractical for highly populated countries. Other architectures are based on Ethereum [27–29], but it is well-known that this blockchain suffers from limited scalability [58]. The architecture based on off-chain storage [30] attempts to address the scalability of Ethereum. However, this work reports a maximum of 124,080 records per hour, but that can only cover 7.1% of the annual demand needed for China. In summary, the scalability of existing blockchains is limited by using a single-layer architecture.

To our knowledge, GEOS represents the first scalable model of a blockchain system for global vaccination records. This scalability is accomplished by using a two-layer blockchain with a low-complexity consensus algorithm to accommodate the vaccination records and statistics of multiple countries. We build an analytical model of GEOS. The model encompasses critical components such as vaccination record volume, communication network, number of validators, block size, and security level of the consensus process. We demonstrate the significance of these parameters in assessing the scalability of GEOS as a blockchain-based vaccination system at a global scale.

3. Proposed system

The proposed system uses a two-layered architecture; the lower layer is for recording the vaccinations of individuals at the national level, and the upper layer is for enabling global interoperability and aggregation of vaccination data statistics. Fig. 1 depicts the architecture of GEOS. The lower layer of the architecture comprises consortium blockchains, referred to as National Immunization Blockchains (NIBs) [59]. The upper layer comprises the Global Immunization Blockchain (GIB). Validators within the NIBs and GIB are interconnected through permissioned P2P networks. The number of validators within each NIB can be equivalent to the number of states or regions within a nation. In contrast, the number of validators within GIB is determined by the count of global health stakeholders involved in the system.

Table 1
Theoretical review of related work on vaccination blockchain-based systems.

Study	Objective	Scalability analysis	Year
Yong et al. [47]	Prevent vaccine fraud and detect vaccine expiration	None	2020
Eisenstadt et al. [26]	Facilitate instant verification of COVID-19 tests and vaccinations	Limited	2020
Mashamba et al [54]	A tracking system using AI for self-tests of COVID-19	None	2020
Ramirez et al. [48]	Secure tracking and delivery control of COVID-19 vaccines	None	2020
Nguyen et al. [55]	Improve the detection of outbreaks and management of medical data	None	2021
Abuhashim et al [27]	Global issuance and verification of vaccination certificates and proofs	Limited	2021
Alabdulkarim et al. [56]	Sharing and verifying COVID-19 information between countries	None	2021
Antal et al. [28]	Tracing of COVID-19 vaccine registration, storage, delivery, and reports	Limited	2021
Biswas et al. [57]	Secure real-time global sharing of COVID-19-related data	None	2021
Loss et al. [29]	Interoperability among health systems for globally sharing COVID-19 data	Limited	2021
Abid et al. [30]	A privacy-preserving COVID-19 platform for test/vaccine certificates	Limited	2022
This work	Record vaccinations at the country and global levels	Global	2023

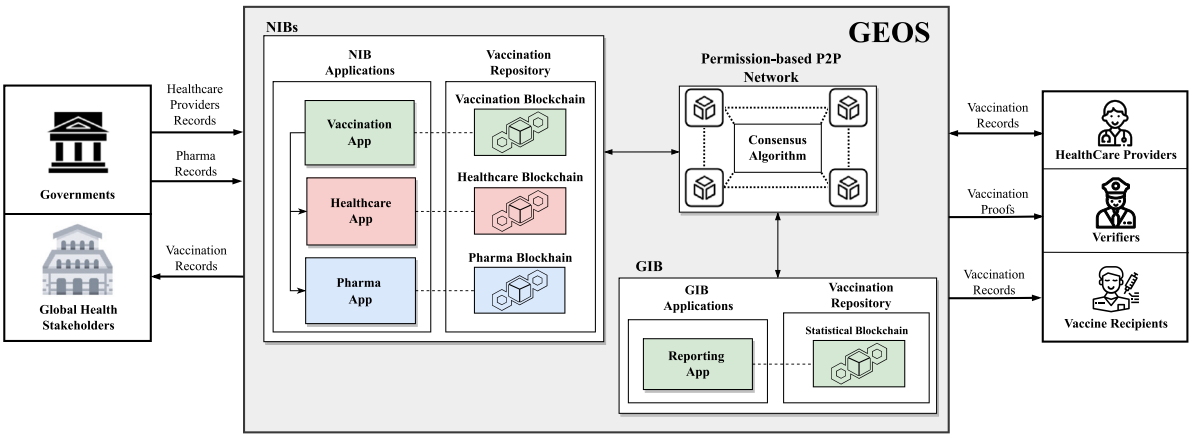

Fig. 1. Components of GEOS, multiple NIBs and a GIB, both use a permissioned P2P network to interconnect with their validators.

Different from the existing blockchains, GEOS is an integrated solution that cross-operates with other two blockchains: (a) vaccine manufacture and distribution management and (b) certified staff verification, as the figure shows. This cross-operational capability empowers GEOS to ensure the secure and interconnected recording of vaccination records, thereby establishing a comprehensive verification framework encompassing data pertaining to healthcare providers and administered vaccines. Consequently, GEOS functions as an all-encompassing blockchain system that streamlines the accessibility of verified vaccination records, effectively validating the authenticity of vaccines, healthcare providers, and vaccination records within its framework.

3.1. Operation of NIB and GIB

An NIB serves as a local repository for vaccination records of a nation's population. To enhance system usability, applications utilizing smart contracts enable access to all three blockchains for recording information. The vaccination application not only allows authorized stakeholders to generate vaccination records but also provides the ability to query records. Vaccine recipients can utilize this application to access their records anytime and anywhere. Furthermore, official agencies may employ the vaccination application to query records or statistics and inform the population about pending vaccinations.

The healthcare application incorporates an access control mechanism that authorizes certified healthcare workers to create or access records in the vaccination blockchain based on their granted attributes and permissions. The pharma application includes methods to record approved batches of vaccines, prevent vaccine reuse, and initiate batch withdrawals in case of recalls. Additionally, it effectively combats counterfeiting and cloning of vaccines, ensuring their authenticity before they reach vaccine recipients.

The GIB adopts a similar architecture to that of a National Immunization Blockchain (NIB), utilizing a network of validation nodes distributed across different countries. GIB ensures interoperability among NIBs by authenticating the validators associated with each NIB. Through GIB, an NIB can request vaccination proof from a foreign NIB on behalf of an individual, which is then verified by validating the digital signature of the signing validators in the received proof. Additionally, GIB plays a crucial role in standardizing the information provided by NIBs, including statistics reported by NIBs and data required for individuals traveling to different regions or countries. Furthermore, GIB incorporates a global reporting application that facilitates the sharing of statistics to identify epidemics or other public health concerns.

Vaccine recipients, healthcare providers, and vaccination verification officers are potential users of NIBs, while international institutions such as the World Health Organization (WHO), UNICEF, and the United Nations may access GIB as users to obtain global vaccination statistics from individual NIBs. Data within GEOS is stored in the form of disaggregated transactions that are committed to the blockchain. Validators in both NIBs and GIB execute applications that employ smart contracts to verify and query vaccination records and statistics, respectively. However, our primary focus lies in the consensus algorithm utilized for transaction verification and recording.

3.1.1. NIB and GIB transactions

In an NIB, a healthcare provider initiates a transaction to record a vaccination. This transaction within the NIB contains essential information, including the vaccine recipient's identification and the administering healthcare provider, as well as details about the vaccine itself, such as its name, serial number, and manufacturer. Validators within the NIB preserve these transactions in their respective vaccination blockchains, ensuring the availability of this data to authorized users.

Listing 1 shows an example of the contents of an NIB transaction.

Listing 1: Example of contents in an NIB transaction.

```
{
    "txId": "<Hash of transaction>",
    "timestamp": "<UTC Time of message creation>",
    "recipient": {
        "Id": "<Vaccine recipient public key>",
        "cc": "<Country code>"
    },
    "vaccine":{
        "vaccode": "<Vaccine code>",
        "route": "<Route of administration>",
        "timestamp": "<Time of administration>"
        "dose": "<Dose's number>",
    },
    "manufacturer":{
        "name": "<Vaccine manufacturer's Id>",
        "cc": "<Manufacturer's country code>",
        "vacname": "<Vaccine's name>",
        "serialnum":"<Vaccine's serial number>",
        "lotnum":"<Vaccine's batch number>"
    },
    "healthcare": {
        "name": "<Healthcare provider's name>",
        "location": "<Healthcare provider's address>",
        "cc": "<Country code>"
    },
    "signerID": "<The public key of healthcare provider>",
    "sig": "<Signature of healthcare provider>"
}
```

GIB transactions are notifications issued by NIB validators to report vaccination statistics to GIB. The information in a GIB transaction may include the number of administered vaccinations, vaccine names, and eligible and anonymous information of vaccinated individuals. GIB validators authenticate the NIB validators, verify the GIB transactions, and commit them to their statistical blockchain.

Listing 2 shows an example of the contents of a GIB transaction.

Listing 2: Example of contents in GIB transaction.

```
{
    "txId": "<Hash of transaction>",
    "timestamp": "<UTC time of report creation>",
    "cc": "<NIB's country code>",
    "report": ["<Statistics of administered vaccinations>"
        ],
    "Q": {
        "QId": ["<Signing NIB validators' membership Ids>"]
            ,
        "aggSig": "< Quorum aggregated signature>"
    },
    "signerId": "<Public key of the sender NIB validator>",
    "sig": "<Signature of sender NIB validator>"
}
```

3.2. P2P network

NIBs and GIB use a permissioned P2P network, as shown in Fig. 2.

The P2P networks are structured overlay networks that communicate through the Internet using the Kademlia protocol [60–62]. The consensus process uses this protocol for broadcasting transactions, blocks, and associated messages. This protocol reduces the number of broadcast messages by enabling validators to share broadcast responsibility.

3.3. Consensus process

NIBs and GIB use the Hotstuff consensus algorithm [63]. This consensus algorithm not only provides byzantine tolerance but also reduces communication complexity by making the leader validator the communicating point instead of performing all-to-all communications.

NIBs and GIB also use the BLS cryptographic signature scheme [35, 64] to aggregate the signatures of multiple validator votes in each phase of Hotstuff. Using BLS in Hotstuff minimizes message communications overhead during the consensus process. BLS reduces the size of the required cryptographic signatures used in each consensus phase.

The consensus algorithm in GEOS operates through four distinct phases: Prepare, Pre-commit, Commit, and Decide, as illustrated in Fig. 3. During each consensus run, a leader is selected in a round-robin manner from among all validators. In each phase, the leader broadcasts a quorum certificate, denoted as Q, to the validators. This certificate contains a list of votes received by each validator in that phase, which are verified by the validators. After verification, the validators respond with their votes. The consensus process progresses from one phase to the next when the leader receives a quorum size, denoted as q_s, of at least two-thirds of the validator votes in each phase. We have chosen the two-thirds threshold for the voting procedure as it ensures the tolerance of the consensus process against Byzantine attacks [65].

The quorum certificate summarizes the 2/3 validator votes and includes the identifications of the voting validators, Q_{Id}, and a BLS aggregate signature of the validator votes, Σ_q. Fig. 4 shows the operations and messages exchanged in a consensus run between a leader and each validator.

In the Prepare phase, the leader broadcasts Q of the last block added to the blockchain. Used as a synchronization phase, validators respond with a vote after positive verification. Then, the consensus process moves to the Pre-commit phase, where the leader broadcasts Q and a block that includes the new transactions for verification. After verifying the transactions, validators respond with their votes. After reaching a quorum in the Pre-commit phase, the process moves to the Commit phase. In the Commit phase, the leader broadcasts Q with the aggregated signature of the quorum in the Pre-commit phase for verification. After reaching a quorum in the Commit phase, the process moves to the Decide phase, where the leader broadcasts Q that includes the aggregated signature of the quorum in the Commit phase for verification. The Decide phase ends after reaching a quorum; once the leader receives 2/3 votes and commits the block to the NIB.

In an NIB, the leader includes a GIB transaction along with the Pre-commit message when sending it to the NIB validators. The NIB validators verify the vaccination statistics of the GIB transaction and send a vote to the leader after verification. The NIB leader then sends the GIB transaction, along with the quorum certificate (Q), to the GIB validators for further verification. The GIB validators verify the aggregated signature within Q and report the statistical information to GIB. The verification process of a newly proposed block in both NIBs and GIB is illustrated in Fig. 5.

3.4. Recording and accessing vaccination records

Generation of NIB and GIB transactions. Fig. 6 shows the steps for adding a transaction to the NIB and reporting statistics to GIB. A healthcare provider, certified by the healthcare blockchain, confirms the identity of the vaccine recipient and administers the vaccine. After that, the healthcare provider issues an NIB transaction, which in turn is sent to a validator and the leader. The leader includes the NIB transaction in a block for the consensus process. The NIB transaction is confirmed once its block is committed to the vaccination blockchain.

Vaccination Verification. GEOS provides authorized verifiers with fast and ubiquitous access to vaccination records or NIB transactions. Fig. 7 shows the vaccination verification process of an individual.

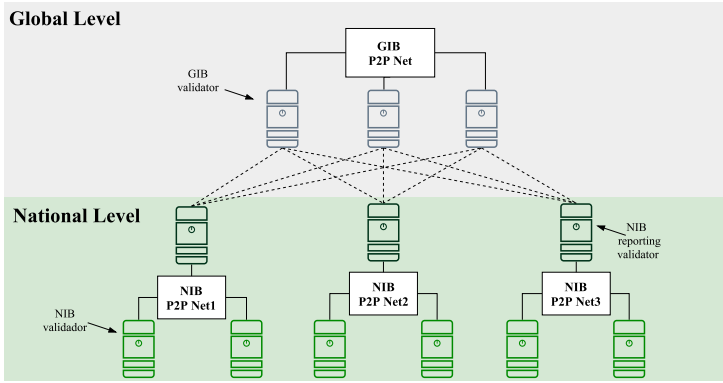

Fig. 2. Architecture of the permission-based P2P network of validators used in GEOS.

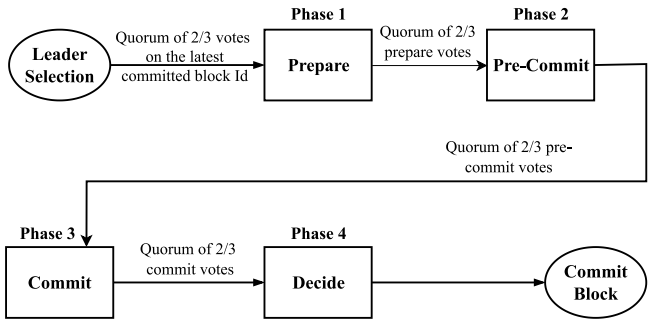

Fig. 3. Phases of the consensus process that NIBs and GIB use on vaccination data.

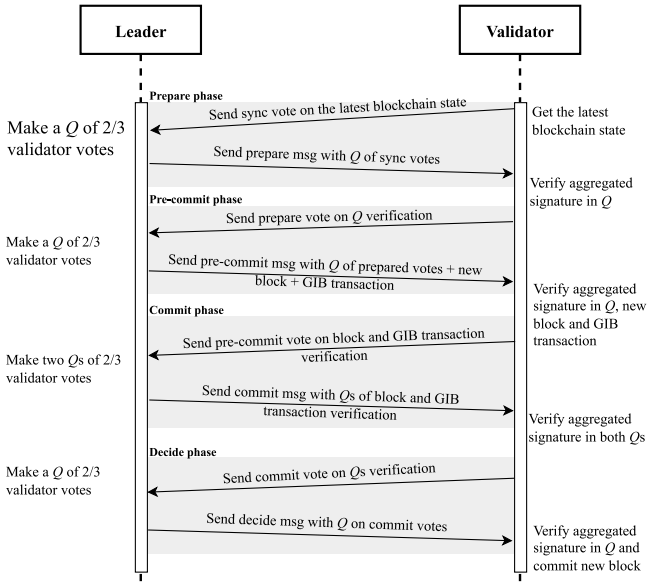

Fig. 4. Communications and operations performed between a leader validator and a validator in the consensus process of an NIB.

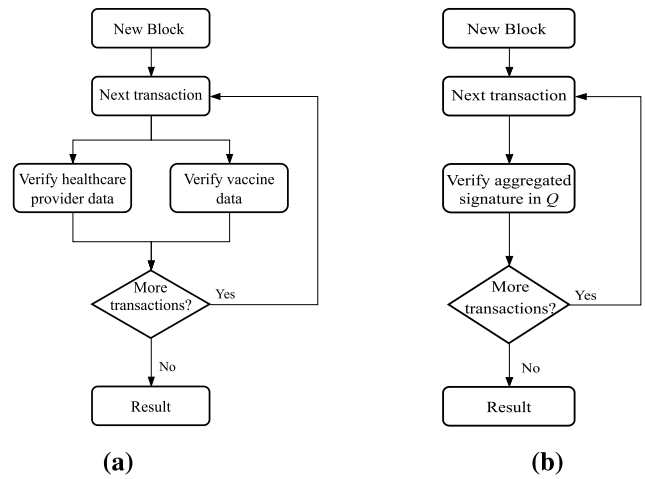

Fig. 5. Block verification in (a) an NIB and (b) GIB.

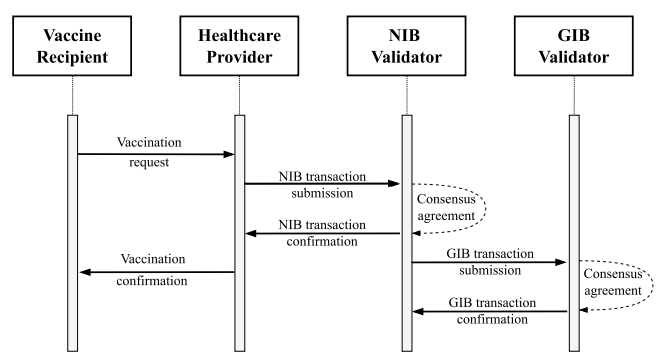

Fig. 6. Process of adding a transaction to NIB and issuing a GIB transaction to GIB.

4. Methods

The latency of the communications in the consensus process determines the transaction confirmation times of an NIB and the GIB, and affects the maximum transaction rate and scalability of the system. In an NIB, the confirmation time of a transaction is the elapsed time from the moment a transaction is sent from the healthcare provider to the moment when the addition of the NIB transaction to the blockchain is confirmed. In GIB, the confirmation time of a transaction is the elapsed time from the moment a GIB transaction is issued by an NIB validator to the moment when the addition of the GIB transaction to the GIB blockchain is confirmed. We modeled the communications performed during the consensus process of NIB and GIB and the confirmation time. Table 2 presents the notations used to describe the confirmation time.

The used BLS scheme employs a pairing function or bi-linear mapping $\mathbf{e}(.)$ and a hash function, $\mathbf{H}(.)$ that uses the BLS12-381 pairing-friendly elliptic curve for both the mapping and the hash function [66]. A validator v generates a random private key, s_{k_v}, and computes its public key, p_{k_v}, by multiplying its private key and a generator point, C_g, on the selected elliptic curve. Validators also aggregate their public keys to create a group public key, p_{k_B}, to verify the aggregated

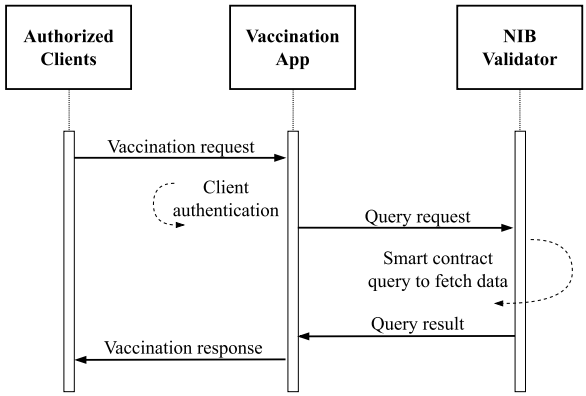

Fig. 7. NIB vaccination verification process.

Table 2
Notations used to describe and analyze GEOS's confirmation time.

Variable	Description
s_{k_v}	Private key of a validator v.
p_{k_v}	Public key of a validator v.
C_g	A generator point in an elliptic curve.
p_{k_B}	Group public key of validators in a blockchain.
Id_v	Membership Id of a validator v.
m_{k_v}	Membership public key of a validator v.
Q	Quorum certificate.
q_s	Quorum size of validator votes.
σ_v	Signature vote of a validator v.
m	A message used in a consensus phase.
Σ_q	BLS aggregate signature from q_s validator votes.
Q_{Id}	Set of Ids of signing validators in Q.
p_{k_q}	Aggregated key of a quorum of validators.
B	A blockchain ledger with $\|B\|$ committed blocks.
b_i	The ith committed block to B.
b_h	Block header, with size $\|b_h\|$, of a block.
b	The largest block size in bytes.
R_i	The set of $\|R_i\|$ transactions in b_i.
$\|R\|$	Maximum number of transactions in a block.
$\|tx\|$	Size in bytes of a vaccination transaction.
tx_{ij}	The jth vaccination transaction in R_i.
M	The validators' memory pool with $\|M(t)\|$ transactions at time t.
n	The number of validators in an NIB or GIB.
$\overline{\|R\|}$	Average number of transactions per block.
ϕ	NIB transaction verification time.
γ	Number of reported GIB transactions per NIB block.
τ_i	Block time of b_i.
T	Average block time.
Θ	Average transaction throughput.
D	Average transaction confirmation time.

signatures in Qs(1).

$$p_{k_B} = \sum_{v=1}^{n} a_v p_{k_v}, \quad a_v = \mathbf{H}\left(p_{k_v}, p_{k_1} \| p_{k_2} \dots \| p_{k_n}\right) \tag{1}$$

Before bootstrapping NIBs or GIB, validators generate their Ids and keys. Membership Ids help identify signing validators in Q during the consensus process. Validators use their membership keys to vote. A validator v generates its membership key, as in (2).

$$m_{k_v} = \sum_{v=1}^{n} (a_v \cdot s_{k_v}) \cdot \mathbf{H}(p_{k_B}, Id_v) \tag{2}$$

Let m be a message holding the contents and Q of a consensus phase. After verifying Q, a validator signs m using its private key, the group public key, and the membership key, as in (3), and it sends its signature (in a vote) to the leader validator.

$$\sigma_v = s_{k_v} \cdot \mathbf{H}\left(p_{k_B}, m\right) + m_{k_v} \tag{3}$$

Here, Q is represented as a two-tuple (Q_{Id}, Σ_q), where Q_{Id} is a set holding the membership Ids of the signing validators in Q, and Σ_q is the aggregated signature from the validator votes. A validator verifies Σ_q in Q using the membership Ids, the group public key, and an aggregated key generated from the public keys of validators in the Q, p_{k_q}, as in (4).

$$\mathbf{e}(C_g, \Sigma_q) = \mathbf{e}\left(p_{k_q}, \mathbf{H}\left(p_{k_B}, m\right)\right) \cdot \mathbf{e}\left(p_{k_B}, \sum_{v \in ID_{q_v}} \mathbf{H}\left(p_{k_B}, ID_v\right)\right) \tag{4}$$

NIB and GIB use a ledger B distributed among n validators. Block b_i, proposed at time t, is the ith committed block in B(5). The subscript i in b_i indicates the block's position in B. Block $b_0(t)$ is the genesis block that stores configuration parameters on what the validators agree beforehand. These parameters are the membership Ids and public keys of all validators, the group public key of the blockchain, the maximum block size, and the smart contracts.

$$B = \left\{b_0(t), b_1(t), \dots, b_i\right\} \tag{5}$$

Here, b_i contains a block header, b_h, and a set of vaccination transactions, R_i. The block header contains metadata to cryptographically link the block to B and a hash of the contents of the block to protect the transaction integrity. Validators verify every transaction in R_i. Here, tx_{ij} in R_i(6) denotes the jth transaction in b_i.

$$R_i = \left\{tx_{i1}, tx_{i2}, \dots, tx_{ij}\right\} \tag{6}$$

Validators use a memory pool, M, to keep the incoming transactions in a First-In-First-Out (FIFO) queue. A transaction awaits in the FIFO queue until the leader in a consensus run includes it in a new block. At the time t, the memory pool of a validator has $|M(t)|$ queued transactions. The maximum number of transactions, $|R|$, in a new block is defined as a function of b, $|b_h|$, and $|tx|$. Here, b is the largest block size indicated in the genesis block, and $|tx|$ is the size in bytes of a transaction. The number of transactions in a block at time t, $|R_i|$, is determined by the number of transactions in the validator's memory pool at that time and $|R|$, as in (7).

$$|R_i| = \begin{cases} |R| & \text{if } |M(t)| > |R| \\ |M(t)| & \text{otherwise} \end{cases} \quad i > 0 \tag{7}$$

The average number of transactions per block, $\overline{|R|}$, in B with $|B|$ committed blocks, is described in (8).

$$\overline{|R|} = \frac{\sum_{\forall b_i \in B} |R_i|}{|B|} \quad i > 0 \tag{8}$$

The consensus latency or block time of b_i, τ_i, is defined as the time validators take to reach a consensus on that block. The average consensus latency, T, over the entire B is defined in (9).

$$\mathrm{T} = \frac{\sum_{b_i \in B} \tau_i}{|B|} \quad i > 0 \tag{9}$$

The average transaction throughput, Θ, is defined as the ratio of the average number of transactions per block and the average consensus latency, as described in (10).

$$\Theta = \frac{\overline{|R|}}{\mathrm{T}} \tag{10}$$

A validator receives a transaction from a user at time δt^r_{ij} and confirms receipt at time δt^c_{ij} after reaching consensus on the block that includes the transaction. We calculate the average transaction confirmation time, D, from the confirmation times of the transactions committed to B, as in (11).

$\forall\, b_i \in B,\ tx_{ij} \in R_i$:

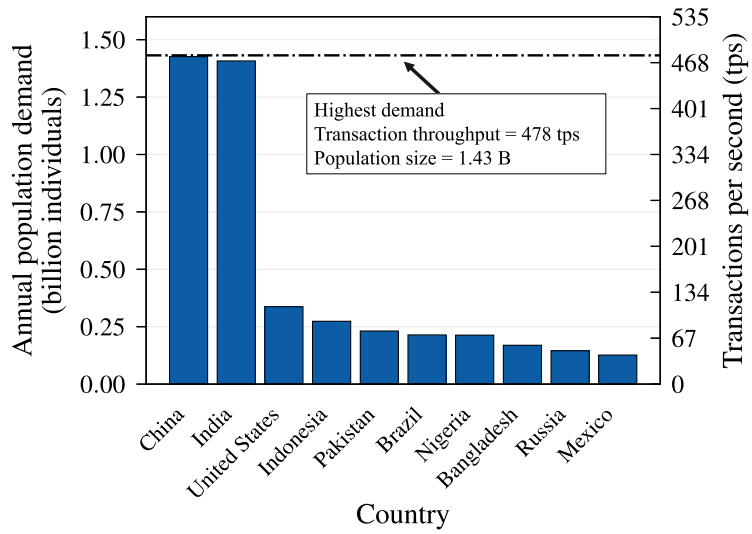

Fig. 8. Top 10 countries that require the highest vaccination rates [67,71].

$$D = \frac{\sum_{b_i}\sum_{tx_{ij}}\left(\delta t^c_{ij} - \delta t^r_{ij}\right)}{\sum_{b_i}|R_i|} \qquad i > 0 \tag{11}$$

5. Results

We analyze the performance and scalability of GEOS by numerically evaluating the average block time, transaction throughput, and confirmation time of NIBs and GIB. We consider 236 NIBs, each corresponding to a member country of the WHO [67]. Without losing generality, we consider the following assumptions in the evaluation:

The consensus algorithm uses a partially synchronous communication model, and it has a bound communication latency [68]. In NIBs, the network bandwidth is 100 Mbps with a validator-to-validator propagation delay of 20 ms [69]. In GIB, the network bandwidth is 50 Mbps with a validator-to-validator propagation delay of 120 ms [70].

The expected annual number of transactions of each NIB comprises the entire population of a country with 2.5 vaccine doses per person [71]. The population size of each country is obtained from WHO [67]. The average transaction rate for each NIB is defined as the ratio of the expected annual number of transactions for each country and the working hours of a day. Here, we consider 260 working days per year and 8-hour workdays. Fig. 8 shows the top 10 most populous countries, and they require the highest vaccination rates. China has the highest demand, with 478 transactions per second (tps) to cover the annual population of 1.43 billion.

5.1. Evaluation of NIB

For each NIB, we assume that the transaction generation follows a Poisson distribution with an average arrival rate equal to the NIB's average transaction rate and the time to verify an NIB transaction is equal to 0.1 ms [72]. Fig. 9 shows the evaluation results of an NIB for China.

Average block time.
Fig. 9(a) shows that the average block time increases as the number of validators increases. This is attributed to the additional time required to reach a consensus with a larger number of validators. As the block size increases, the average block time increases because the block includes more transactions, subsequently leading to an increase in block verification time. However, for NIBs with fewer than 32 validators, the block size does not significantly impact the average block time. Conversely, for NIBs with 64 or more validators, increasing the block size from 1 to 4 MB results in a three-fold increase in the average block time. It is worth noting that the increase in block time for NIBs with more than 64 validators may be justified by the corresponding increase in transaction throughput, which enables the recording of vaccination data for a larger number of individuals.

Average transaction throughput. Fig. 9(b) shows that the average transaction throughput decreases as the number of validators increases. Similarly, as above, the decrease occurs because the number of validators increases, and it takes longer to get a quorum in each consensus phase. The transaction throughput exhibits an upward trend as the block size increases. Specifically, with 64 validators, increasing the block size from 1 to 4 MB results in an approximate 33% increase in transaction throughput. In scenarios where the smallest number of validators (i.e., four validators) is employed, the average transaction throughput reaches a maximum of 1000 tps, while the minimum value is 235 tps, both observed with 128 validators. It is important to note that there is a trade-off between transaction throughput and system security. Increasing the number of validators enhances the security of the system, albeit at the expense of the system's capacity to record a larger volume of vaccinations.

Average confirmation time. Fig. 9(c) shows that the average transaction confirmation time increases as the number of validators increases. With more than 32 validators, the transaction confirmation time grows because transactions are committed to the vaccination blockchain at a rate slower than the transaction arrival rate. A block size of 1 MB produces the longest average transaction confirmation time. This is the case when transactions experience the longest queuing delay in the memory pools of the validators.

Implementing an NIB with a large block size may effectively reduce the transaction confirmation time. For example, the average transaction confirmation time with 128 validators and 1 MB is more than three hours, but it is reduced to about 1.4 h with a block size of 4 MB.

We also analyze the impact of the transaction verification time, ϕ, on the transaction confirmation time. Transaction verification time is the time it takes to verify a transaction, and that depends on the computing resources of a validator. As these resources may vary, we evaluate the transaction confirmation time with different values of ϕ and the number of validators and 4-MB blocks. Fig. 9(d) shows that the average transaction confirmation time increases as ϕ increases because the verification time increases as the number of transactions waiting in the queues increases. When $\phi \leq 1.0$ ms, the transaction confirmation time remains negligible for 16 or fewer validators and grows as the number of validators increases. When $\phi = 10$ ms, there is

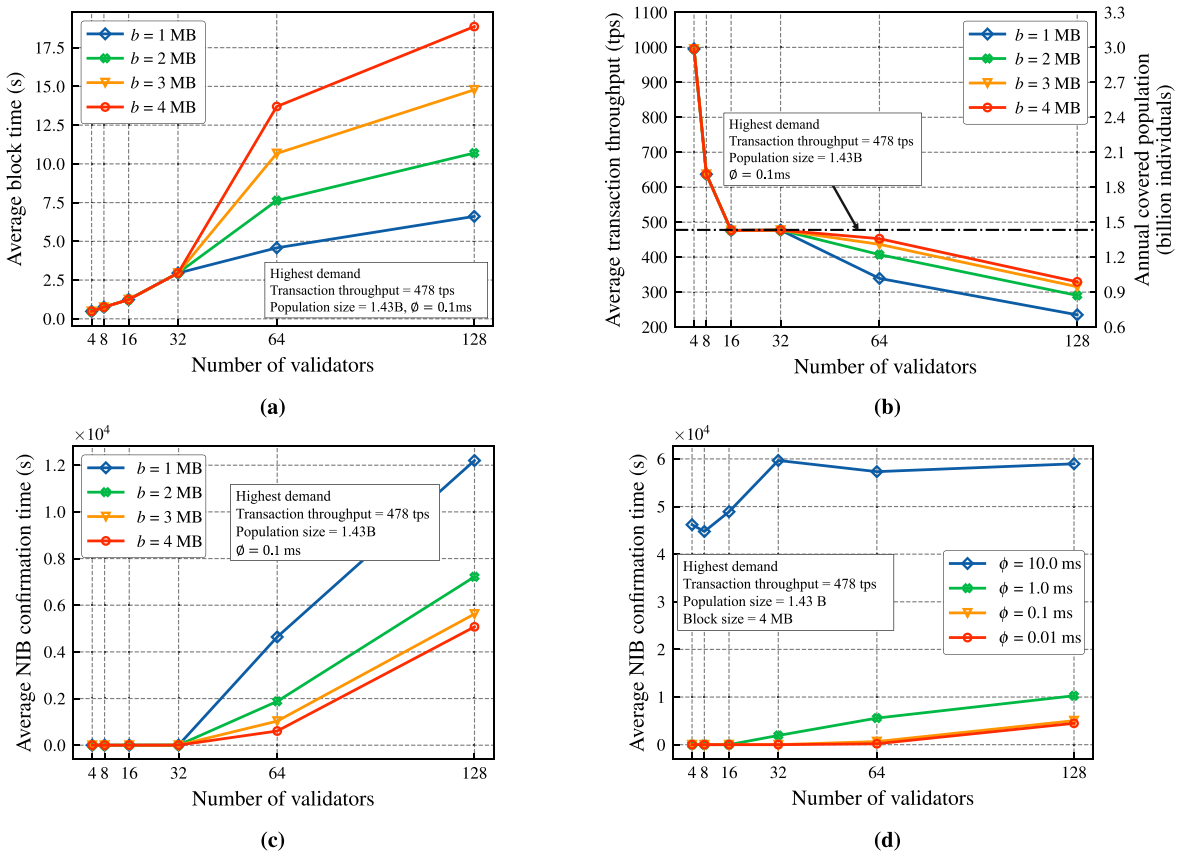

Fig. 9. Estimated performance of daily operations of an NIB for China with an expected vaccination transaction rate of 478 tps: (a) Average block time; (b) Average transaction throughput; (c) Average transaction confirmation time for various block sizes; and (d) Average transaction confirmation time for various transaction verification times, ϕ, each of them as a function of the number of validators.

a large increase in the transaction confirmation time independently of the number of validators.

The highest demand case.

Fig. 9(b) illustrates that an NIB can support the highest demand for China with a network of up to 32 validators, using a block size ranging from 1 to 4 MB, and an NIB transaction verification time of 0.1 ms. Under this configuration, the NIB block time is 2.95 s, as shown in Fig. 9(a), and the transaction confirmation time is 4.1 s, as shown in Fig. 9(c). Additionally, Fig. 9(d) demonstrates that if the verification time of an NIB transaction exceeds 10 ms, a single NIB for China would be unable to sustain the required demand, regardless of the number of validators or block sizes employed due to significant queuing delays experienced by transactions.

5.2. Evaluation of GIB

We assume that the transaction arrival to GIB also follows a Poisson distribution, and the average arrival rate is the sum of the average number of committed blocks per second of all 236 NIBs. This rate renders an average of 1.95 million committed blocks daily, corresponding to an average of 68 tps. We set the number of validators of each NIB in the range of 4 to 64 to accommodate the vaccination rates shown in Fig. 8. Each NIB submits a transaction to GIB for every two committed blocks ($\gamma = 2$) to reduce the rate. The verification time of a GIB transaction is set to 10 ms. Fig. 10 shows the average block time, transaction throughput, and transaction confirmation time of GIB.

Average block time. The average block time increases as the number of validators and the block size increase, as Fig. 10(a) shows. The block time in GIB takes longer than that in an NIB because of the longer communications delay of GIB's consensus process and the longer verification time of a GIB transaction. Increasing the block size allows adding more GIB transactions but also increases the block time.

Average transaction throughput. The average transaction throughput decreases as the number of validators increases and it increases as the block size increases, as shown in Fig. 10(b). The decrease in the transaction throughput can be amortized by increasing the block size. For example, the transaction throughput with 64 validators increases by about 39% by increasing the block size from 1 to 4 MB.

Average confirmation time. The average GIB confirmation time increases as the number of validators increases, as Fig. 10(c) shows. However, it decreases as the block size increases because a larger block size allows more transactions in a block and fewer queued blocks. For example, a 48% improvement in confirmation time is achieved by increasing the block size from 1 to 4 MB with 128 validators.

While it is desirable for GIB to maintain real-time vaccination statistics, the confirmation time of GIB transactions can be improved by adopting a strategy where NIBs generate a single report (GIB transaction) after a certain number of NIB blocks (γ), as depicted in Fig. 10(d) for $\gamma = 1$. Notably, with 4-MB blocks and 128 validators, the average transaction confirmation time significantly increases to over three and five times the confirmation time when NIBs send GIB transactions every two and four committed blocks, respectively.

The highest demand case. GIB can handle the highest annual demand for recording global vaccination statistical data using a network of up to 32 validators and 4-MB blocks, as shown in Fig. 10(b). To achieve this, NIBs should send GIB transactions at least every two committed blocks. Under these conditions, the average block time is 24.72 s, and the transaction confirmation time is 132.43 s, as depicted in Fig. 10(a) and Fig. 10(c), respectively. Furthermore, reducing the GIB transaction rate leads to a decrease in the average GIB transaction confirmation time, as demonstrated in Fig. 10(d).

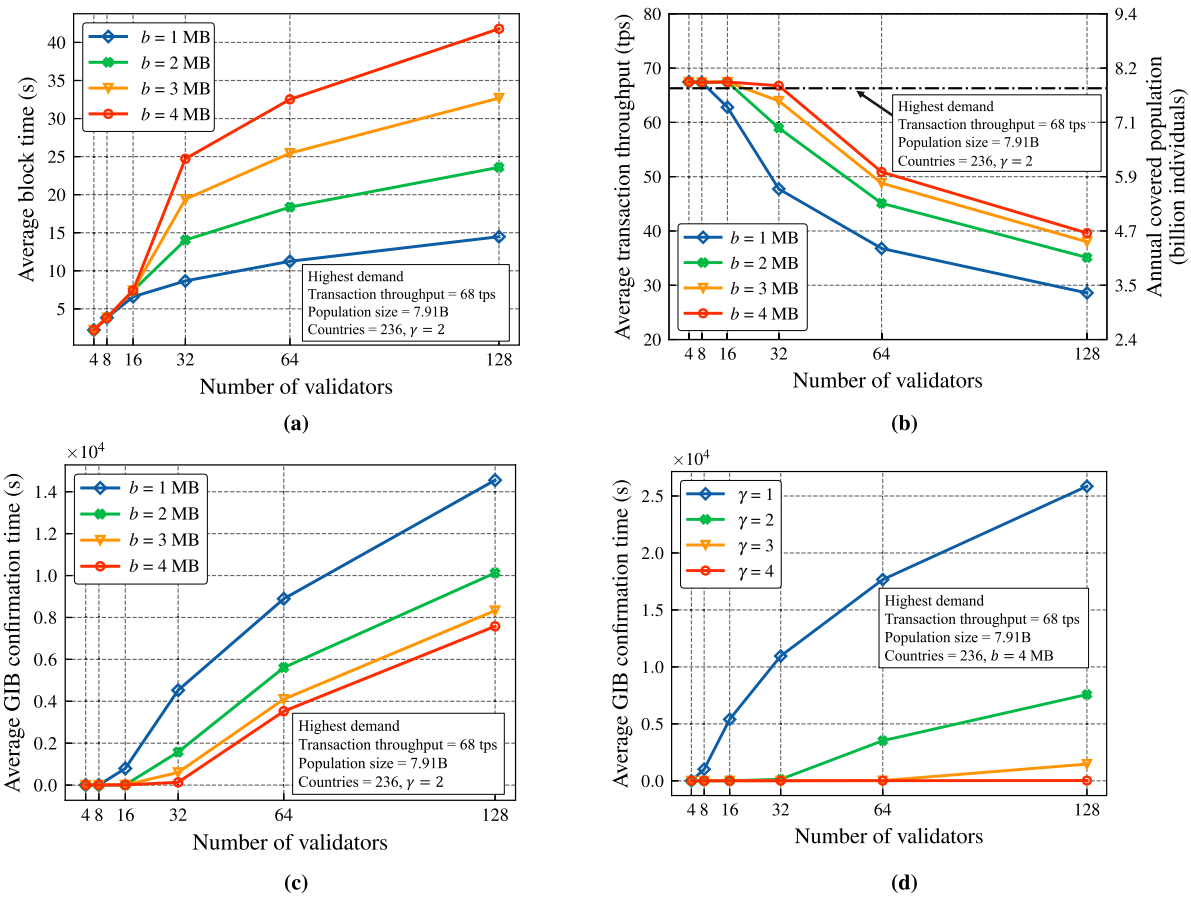

Fig. 10. Estimated performance of GIB for an entire day of operations: (a) Average block time, (b) Average transaction throughput, (c) Average transaction confirmation time, and (d) Average transaction confirmation time with 4-MB blocks and various GIB transaction sending rates, γ, each of them as a function of the number of validators.

6. Discussion

The results show that there is a trade-off between the number of validators and the block size. The transaction throughput decreases as the number of validators increases as the consensus process needs to acquire a larger number of verifications. On the other hand, increasing the block size increases the number of transactions in a block, but it takes longer to verify those transactions. Adding more transactions in a block has a performance gain over the penalty of verifying a larger number of transactions in a block. However, for a large number of validators, a larger block size produces longer commitment times.

Our results indicate that GEOS can be configured to support various demands. The presented evaluation considers that the generation of vaccination records occurs for 8 h per working day. Such an assumption stresses the daily demand for vaccination records, which are reflected in the estimated NIB transaction throughput for satisfying the estimated daily demand of China. In this case, an NIB with up to 32 validators can handle the recording of annual vaccination records for a population of 1.43 billion with 2.5 vaccine doses per person. The 32 validators could be selected from its provinces and autonomous regions [73]. Extending the number of validators for this country would also require expanding the operating hours or the transaction confirmation times. Countries with lower transaction rates can adopt an NIB with more than 32 validators. For instance, an NIB for the United States (113 tps) may require a network with 50 validators, one validator per state.

Owing to using the same architecture as the NIB, GIB is subject to the same trade-offs. However, because the GIB transactions are larger than the NIB transactions, the commitment time may be longer. The results indicate that GIB can handle the recording of annual vaccination statistics from 236 countries, covering a global population of 7.91 billion people. This coverage can be achieved with a network of 32 validators and 4-MB blocks. A GIB network consisting of 32 validators is adequate to cover the six WHO regions, with five validators per region for redundancy. We can further relax the transaction throughput demand if we allow longer time for transactions to be confirmed.

Future research could explore the optimal allocation of validators within a country. In our current study, we took into account the number of provinces or states, recognizing the administrative and political boundaries. However, further investigation is needed to consider the population distribution per province as a relevant factor in the allocation strategy.

Another area that warrants further research is the design of a consensus algorithm that does not penalize the block time as the number of validators increases. This is particularly crucial for populous countries, as they may benefit from scaling up the number of validators without significantly impacting the block time.

The analysis of security features in GEOS is also identified as a future research direction. This analysis would encompass an examination of various cybersecurity attacks that may target the consensus process, including denial of service attacks, spoofing, and elevated privileged attacks.

Another area of interest pertains to the integration of GEOS with off-chain storage solutions aimed at reducing the storage requirements on validators [74–76]. Such a solution would involve offloading committed blocks or vaccination data to off-chain storage while maintaining hash pointers to this data on the blockchain.

An investigation into the trade-off between storage capacity and the time required for retrieving and verifying NIB transactions would be valuable. Additionally, optimizing GEOS to enhance the retrieval speed of global historical statistical data from GIB, which enables

the measurement of vaccination campaign effectiveness and global vaccination coverage, would also be worthwhile.

7. Conclusions

In this paper, we introduced GEOS, to fill the existing gap of a blockchain for recording vaccinations on a global scale for containing a pandemic, such as COVID-19. A global-scale blockchain requires a balance between the autonomy of political regions and interoperation between different regions and yet, a capacity large enough for accommodating both the fast vaccination rate of populous countries and the number of records needed for the world population. GEOS achieves such scalability using a two-layer blockchain architecture and a low-complexity consensus algorithm to overcome the limitations of the single-layer architecture used by existing approaches. It comprises national-level blockchains to record vaccination information and a global blockchain to report vaccination statistics and facilitates the interoperability of vaccination information systems and continuity of care by the secure sharing of vaccination records on a global scale. We developed an analytical model of GEOS to evaluate its performance in terms of transaction throughput and transaction confirmation time under a global demand, as it has been the case for COVID-19. For testing the fastest rate of vaccination demand, we considered a country with the population of China, which requires the recording of vaccinations for 1.43 billion individuals with 2.5 doses per person per year, or 478 transactions per second, and showed that GEOS can support it, even with 32 validators. Furthermore, we have outlined the outstanding challenges that have been identified as potential areas for future research. We anticipate that these challenges will become increasingly crucial as the population continues to expand, emphasizing the need to address them to fully harness the scalability potential of a vaccination recording system.

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